Research on the properties of Wide Span Vehicle in Controlled Traffic Farming

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Abstract. The purpose of the article is to investigate the traction, energy, and coupling properties of Wide Span Vehicles (WSV) during their operation in Controlled Traffic Farming (CTF) conditions. Based on the analysis, systematization, and synthesis of theoretical data, the advantages of using WSVs in CTF conditions have been identified, along with the absence of mechanical and technological foundations for their functioning and utilization. The conducted research has determined that the necessary specific power of WSVs should be 23.5 $W \cdot kg^{-1}$ at 1 $km \cdot h^{-1}$, Their movement on CTF tracks is accompanied by a lower slip value (at the level of 0.15…0.17) compared to their movement on agricultural background, where the wheel realizes the maximum traction contact force, allowing it to develop pulling forces at the level of 6.37 kN per ton of its operational mass. In future studies, we plan to explore the technological properties of WSVs, characterizing their compliance with technological requirements across the entire range of agricultural operations for which they are intended as part of the equipment. Keywords: WSVs, controlled traffic farming, traction and energy properties, experimental studies

1 Introduction

The issue of compacting agricultural fertile soil can be addressed by organizing the movement of traction and transport vehicles across the field [1, 2]. It is known that farmers' transition to Controlled Traffic Farming (CTF) significantly enhances the effectiveness of reducing the compacting impact of wheel tracks on the soil by the movers of agricultural units [3, 4]. A promising further development of CTF involves the utilization of WSV [5, 6]. Implementing CTF principles through the use of WSV can lead to a reduction in unproductive field area under technological tracks to 4…7% [7, 8]. Based on our analysis of publications, it can be concluded that as of today, there is no comprehensive theory or calculation methodology for WSV in the context of Controlled Traffic Farming (CTF) and their individual mechanisms. The traction, energy, technological, and other properties of WSV are entirely determined by the requirements of the conditions in which they operate

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and are defined by their design parameters and technical characteristics. There should be a clear and unequivocal relationship between the indicators of the technological process and the technical characteristics of WSV. The relationship between the structural parameters of WSV and their technical characteristics, as well as their technological indicators, is not as straightforward as the connection between characteristics and indicators. The same structural parameter of a WSV may influence multiple indicators and characteristics. For example, the width of its wheelbase and the parameters of the movers affect all indicators of the technological process and most technical characteristics, except those that are specified and regulated (such as maneuverability, stability of movement, smoothness of travel, etc.). [9, 10]. By correlating the requirements of the technological process with the structural parameters of WSV, it is possible to draw conclusions about the degree of their technological effectiveness. Therefore, the study of the mechanical and technological foundations of the operation and utilization of WSV, as well as the development of methods for analyzing and assessing the compliance of parameters and characteristics with the requirements of CTF technologies, is a relevant task.

From the classical theory of tractors, it is known that the power of a traditional agricultural tractor is primarily realized through traction. However, with the development of tractor and agricultural machinery designs, cultivation technologies, etc., the practice has posed the necessity for the scientific substantiation of theoretical issues in the traction-energy concept of tractor theory [11], in which the effective engine power cannot be fully realized through traction alone. This direction has been developed in works [12, 13], where the expediency of using not just tractors as tractors but lighter and more energy-efficient tractors in agricultural production is justified [14]. Essentially, a WSV should adhere to the traction-energy concept. As the transition from a traditional tractor to a gantry of a WSV with a branched power take-off system for aggregation with technological machines and tools equipped with active working bodies requires an evaluation of their specific power level.

Simultaneously, our research has shown that the movement of WSV along the technological tracks of Controlled Traffic Farming (CTF) allows them to have better traction and coupling properties compared to a traditional tractor moving on agricultural terrain [15]. The nominal tractive effort developed by a WSV, provided there is sufficient coupling of its movers with the supporting surface of CTF tracks, is greater than that of a traditional tractor with the same technical parameters [16]. At the same time, the coupling of the movers of a WSV with the supporting surface of CTF tracks should be sufficient for it to develop maximum tractive effort while operating with a certain level of slip. This is because a lower slip corresponds to a smaller value of traction contact force exerted by the traction and transport vehicle when slip is minimal.

There is no doubt that the movement conditions of WSV on a solid and leveled supporting surface of CTF tracks should result in a significant magnitude of its maximum traction contact force. Unlike a traditional tractor, where the maximum value of this force corresponds to slip, significantly exceeding the level at which undesirable soil damage may occur [17]. Hence, there is a need to search for the next compromise: the maximum slip of the wheelbase of a WSV should be such that, provided there is sufficient coupling with the supporting surface of CTF tracks, it develops the maximum possible traction contact force.

The relevance of these studies is also driven by the fact that the tractor theory does not separately consider the influence of wheel parameters and the physico-mechanical properties of the supporting surface on slip. This influence cannot be adequately examined without taking into account the change in rolling resistance of the movers, which naturally has less significance when the traction and transport vehicle is moving along CTF tracks compared to agricultural terrain.

2 Theoretical Background

The maximum traction contact force P_{kmax}, яку developed by the wheel of a WSV is determined by the conditions of sufficient coupling with the supporting surface of the CTF track [15]:

$$P_{kmax} = \varphi \cdot N_{ek} \,. \qquad (1)$$

where φ – is the coefficient of traction realized by the movers of the WSV under the conditions of its interaction with the supporting surface of the CTF tracks;

N_{ek} – the vertical operational load acting on the wheel of the WSV.

According to condition (1), the wheel's traction must be sufficient for the WSV to develop nominal tractive effort while moving on CTF tracks with a certain level of slip.

On the other hand, the magnitude of the traction contact force P_{kma} , developed by the wheel depends on the normal load acting on it, wheel parameters, physico-mechanical properties of the supporting surface of the CTF tracks, and the mode of its movement (slip coefficient) [16]:

$$P_{kmax} = \delta_{max} \cdot S_k \cdot k_0 \cdot L \,, \qquad (2)$$

where δ_{max} – is the slip coefficient (maximum) of the movers of the WSV;

S_k – the sum of the vertical projections of the supporting surfaces immersed in the soil by the wheel of the WSV, m^2;

k_0 – the coefficient of volumetric soil compaction in the CTF tracks, $N \cdot m^{-3}$;

L – the length of the wheel-soil contact arc of the wheel of the WSV with the supporting surface, m.

3 Research Methods

Experimental studies of the WSV were conducted in a specially created laboratory (Figure 1a) at Dmytro Motornyi Tavria State Agrotechnological University (TSAU). The physical objects of the research were units constructed based on the WSV of TSAU (see Figure 1). The technical characteristics of the WSV of TSAU are presented in [15].

a) b) c)

Fig. 1. Wide span vehicle TSAU as part of agricultural units during experimental studies: a) toothed harrows; b) rotary harrow; c) S-shaped cultivator

Experimental studies were conducted using both widely accepted and developed methodologies [18, 19]. They involved the use of modern strain gauge and specially created equipment for electrical measurements of non-electric quantities. The processing of experimental data was performed on a PC using probability theory, regression analysis, and correlation-spectral analysis [20]. The error of the experimental research results did not exceed 10%.

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4 Results and Discussion

To assess the energy consumption of any WSV moving along CTF tracks, consider the force diagram acting on it (Figure 2). From Figure 2, it can be seen that the WSV is subject to the traction forces P_{kl}, P_{kr} and the hooking forces P_{hl}, P_{hr}, developed by the movers of its left and right sides, as well as the rolling resistance forces P_{fl} and P_{fr}.

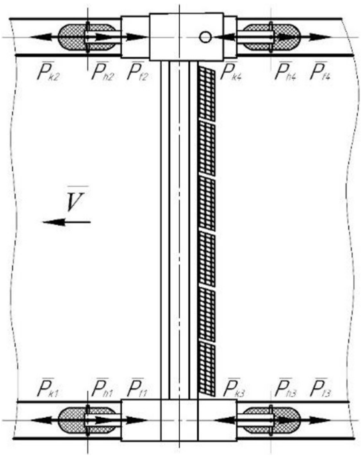

Fig. 2. Equivalent diagram of a WSV moving along tracks

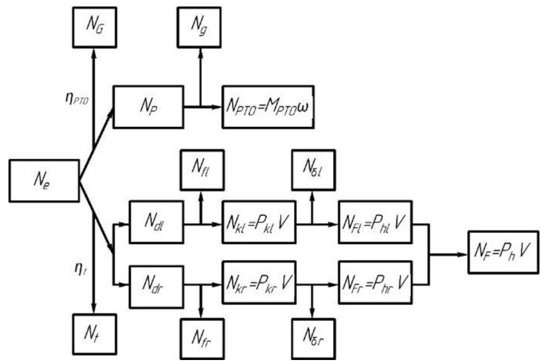

Fig. 3. Structural diagram of the power flow of a WSV

The essence of determining the nominal effective power of the power unit of the WSV, according to the balance of its power, boils down to summing up the useful power and the energy losses due to friction in the transmission, movers slip and overcoming rolling resistance (fig. 3).

In accordance with the provided structural diagram (see fig. 3), the effective power N_e of the power unit of the WSV is realized by transmitting energy through the transmission to drive the movers on its left and right sides, and through the power take-off system to drive the active working elements of technological machines. Due to the power transmission through the transmission, losses N_t occur, which are estimated by the transmission efficiency factor η_t. A portion of the power on the leading wheels of the left and right sides (N_{dl}, N_{dr}) of the WSV is expended to overcome the rolling resistance (N_{fl}, N_{fr}). Power flows on the driving wheels of the left and right sides (N_{kl}, N_{kr}) are used for slip losses ($N_{\delta l}$, $N_{\delta r}$), as well as for useful traction power N_F, determined by the traction force on the hook P_h and the speed of the vehicle V.

During the power transmission process through the power take-off system N_P o the active working elements N_{PTO}, determined by the torque M_{PTO} and angular speed ω of the output shaft of the drive, power losses in the reducer N_G and drive N_g, are taken into account, estimated by the efficiency factor η_{PTO}.

The assessment of the specific power of the WSV TSAU, moving along the technological tracks of CTF, showed a direct proportional dependence on its operating speed:

$$E = 2.3562 \cdot V + \frac{N_{PTO}}{M \cdot \eta_{PTO}} , \tag{3}$$

where M – the mass of the wide span vehicle, kg.

As a result of studying the properties of the wide span vehicle TSAU, it has been determined that its specific power for operating speeds of up to 5 km·h^{-1} is 12.5 W·kg^{-1}, and at speeds of 10 km·h^{-1} its reaches 23.5 W·kg^{-1}. The obtained result of the specific power of the WSV, without considering additional power take-off, exceeds the specific power level of traditional tractors with a traction concept, which is known to be no more than 15.0 W·kg^{-1} [11]. This can be explained by the fact that the WSV, when moving on leveled and compacted CTF tracks, exhibits better traction and grip properties compared to a traditional tractor moving on agricultural terrain. In particular, it has been established that for each ton of operational mass, the WSV should develop a traction force of 6.37 kN, provided there is sufficient coupling of its movers with the supporting surface of the CTF tracks. Therefore, to achieve higher traction forces, a greater tractive power is required, increasing the necessary nominal power of WSV energy systems. Moreover, a distinctive feature of the WSV's movement on CTF tracks is the ability to increase the slip ratio of its movers to 0.15…0.17, which also increases power losses in this process.

The results of the traction and grip properties research of the WSV have shown that increasing the slip ratio δ_{max} allows obtaining a higher maximum traction force it develops under conditions of sufficient coupling with CTF tracks. For example, with the same slip ratio value of δ_{max}=0.22 or the movers of the WSV, at which it develops the maximum traction force on the agricultural field, the coefficient of traction is φ=0.43. However, during its movement on CTF technological tracks, this value increases to φ=0,55. Thus, the movement of the WSV on CTF technological tracks is characterized by an improvement in its grip properties compared to field prepared for sowing.

The experimentally obtained dependence of the traction force on the wheel slip ratio of the WSV showed quite similar results (fig. 4).

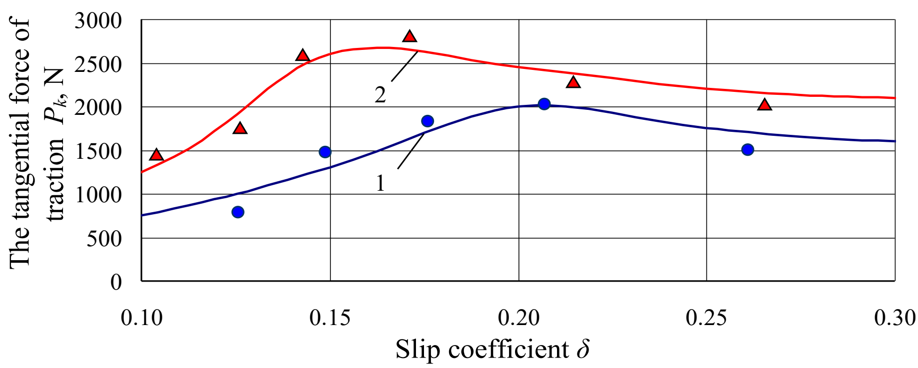

Fig. 4. The dependence of the traction force P_k of the wheel of the WSV TSAU on the slip coefficient δ_{max} during its movement on the agricultural background prepared for sowing (1) and on the CTF tracks (2)

Based on the analysis of Figure 4, it can be concluded that the traction force of the WSV, increases until the slip ratio coefficient reaches a certain value. After reaching this value, the traction force starts to decrease with further increase in slip ratio. The reduction in traction force at higher wheel slip of the WSV is explained by the fact that soil clods are sheared, compressed between the ground engaging elements, and rotate with the wheel. Since the shear stress during sliding is less than the maximum static stress, the traction force of the WSV wheel is reduced.

The slip ratio level δ_{max}, at which the maximum traction force is developed for the WSV wheel on the agrofone field, prepared for sowing, is in the range of 0.22…0.24. At this point, the magnitude of this force is approximately 2.0 kN. For the track of the CTF, the maximum slip ratio coefficient δ_{max} decreases to 0.15…0.17 with an increase in the maximum traction force to 2.65 kN, which the wheel of the wide span vehicle develops.

The conducted research has proven that the wheel rolling of the WSV on the CTF track is accompanied by a smaller slip, at which the wheel realizes a large traction force. As a result, the WSV loses less speed, and less energy is expended. It has been established that under the conditions of the WSV moving on the agrofone field prepared for sowing, the maximum traction force of the wheel is developed at a slip ratio of 0.22…0.24. And when moving on CTF tracks, this value decreases to 0.15…0.17. With an increase in the hardness of the CTF technological tracks from 1.0 to 3.5 MPa, the air pressure in the wide span vehicle TSAU wheel tire needs to be increased from 60.0 to 650 kPa, which is 10 times. Naturally, the magnitude of the maximum allowable air pressure in the tire is determined by its technical specification. For the specified brand of tire used in the WSV TSAU, this value is 160 kPa. Therefore, its operation with the maximum tire pressure is possible only with a track hardness of CTF of 2.25 MPa and above. However, at lower hardness of the ground track, the air pressure in the wheels should be reduced. This allows ensuring high traction properties of the WSV when moving on the ground track of CTF. For example, with a hardness value of 1 MPa, the tire pressure of the wide span vehicle TSAU wheels should be 80 kPa.

The conducted research confirms the fact that the maximum efficiency of the WSV movement on technological tracks of CTF can only be achieved with the correctly set air pressure in its tires. The magnitude of the latter, in turn, depends on the physical and mechanical properties of the technological tracks of CTF.

5 Conclusions

The conducted research has established that for the full realization of the traction and energy properties of WSV at operating speeds up to 5 $km \cdot h^{-1}$ their specific power should be 12.5 $W \cdot kg^{-1}$, and within the range up to 10 $km \cdot h^{-1}$, it is 23.5 $W \cdot kg^{-1}$. Therefore, in real operating conditions, reducing the working speeds of these vehicles is a way to reduce energy consumption in CTF.

Under the condition of sufficient coupling of the movers of WSV with the supporting surface of the technological tracks CTF, it allows them to develop traction forces at the level of 6.37 kN per ton of their operational mass. This is 1.4 times more than a traditional wheeled tractor can develop when moving on a plowed agricultural background.

The movement of WSV on the ground track CTF, unlike the agricultural background, allows an increase in its coefficient of traction to 0.55. In this case, the maximum traction force developed by its wheels is achieved with a smaller amount of slippage, reaching a level of 0.15...0.17. Practically, this means that the movement of WSV on a leveled and compacted ground track CTF allows an improvement in its traction properties by at least 30%.

The movement of WSV on CTF tracks is accompanied by a smaller amount of slippage (within the range of 0.15…0.17), unlike its movement on an agricultural background prepared for sowing (0.22…0.24), where the maximum traction force is realized by the wheel. This allows for less loss of working speed, resulting in lower energy consumption.

The movement of WSV on CTF tracks is accompanied by a larger maximum traction force (improving by at least 30%) compared to its movement on an agricultural background prepared for sowing. This enhances its traction properties compared to a traditional tractor operating on an agricultural background.

The movement of WSV on CTF tracks is accompanied by high traction properties (the coefficient of traction increases from 0.43 to 0.55) compared to its movement on an agricultural background prepared for sowing. This fact practically limits the widespread use of ballasting for WSV, unlike traditional tractors, in order to improve their traction properties.

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